Available online at www.sciencedirect.com
ScienceDirect
Renewable and Sustainable Energy Reviews 13 (2009) 583–593
RENEWABLE & SUSTAINABLE ENERGY REVIEWS
www.elsevier.com/locate/rser

Sustainability evaluation of decentralized electricity generation

Cornelia R. Karger *, Wilfried Hennings

Research Centre Jülich, Programme Group Humans, Environment, Technology (MUT), 52425 Jülich, Germany

Received 8 August 2007; accepted 7 November 2007

Abstract

Decentralized power generation is gaining significance in liberalized electricity markets. An increasing decentralization of power supply is expected to make a particular contribution to climate protection. This article investigates the advantages and disadvantages of decentralized electricity generation according to the overall concept of sustainable development. On the basis of a hierarchically structured set of sustainability criteria, four future scenarios for Germany are assessed, all of which describe different concepts of electricity supply in the context of the corresponding social and economic developments. The scenarios are developed in an explorative way according to the scenario method and the sustainability criteria are established by a discursive method with societal actors. The evaluation is carried out by scientific experts. By applying an expanded analytic hierarchy process (AHP), a multicriteria evaluation is conducted that identifies dissent among the experts. The results demonstrate that decentralized electricity generation can contribute to climate protection. The extent to which it simultaneously guarantees security of supply is still a matter of controversy. However, experts agree that technical and economic boundary conditions are of major importance in this field. In the final section, the article discusses the method employed here as well as implications for future decentralized energy supply.

Keywords: Distributed generation; Electric power supply; Sustainability; Multicriteria analysis

Contents

* Corresponding author. Tel.: +49 2461 612794; fax: +49 2461 618173.
E-mail address: c.karger@fz-juelich.de (C.R. Karger).

1364-0321/$ – see front matter
doi:10.1016/j.rser.2007.11.003

1. Introduction

To date the electric power supply in Germany and other industrialized countries has been characterized by large power stations and a hierarchically organized grid structure. Recently, however, decentralized electricity generating plants have been attracting increasing interest. A shift towards decentralized technology can be observed in many industrialized countries [1–4]. The reasons for this are the deregulation of the electricity markets, problems with licensing new high-voltage transmission lines, increasing demand for a highly reliable power supply and, in particular, the problems associated with climate change [1]. In Germany, it seems possible that centralized plants may be replaced by decentralized facilities since in the near future a considerable number of old plants will have to be replaced by new ones. For example, in its final report [5], the select committee of the German Bundestag concerned with the ‘‘Sustainable Energy Supply’’ estimated on the basis of the previously recorded lifetimes of power plants that between 2010 and 2025 new power plant capacities of 40–60 GW will have to be constructed. The question therefore arises of whether decentralization is indeed beneficial.

1.1. What is decentralized electricity generation?

First of all, decentralized electricity generation means ‘‘an electric power source connected directly to the distribution network or on the customer side of the meter’’ [6]. This means that the electric energy only needs to be transported over short distances, thus reducing transportation losses. The most common technical term is ‘‘distributed generation’’ (DG).

Although this definition does not define the size of the generation source, the point of connection to the network actually limits the power which can be fed into this network level. Ackermann et al. suggest that a distinction should be made between micro-DG (unit size below 5 kW), small DG (5 kW to 5 MW), medium DG (5–50 MW) and large DG (50–300 MW). In the U.S.A. the term ‘‘distributed utility’’ is also used, which includes not only local generation but also local storage and local demand side management [7].

In our study, decentralized electric power generation is described by the contribution of combined heat and power units (CHP) (micro and small) to overall electric power generation and by the introduction of virtual power plants.

Second, while most publications about distributed generation [1,7–9] assume that the decentralized generation units feed into the existing, hierarchically structured distribution network, decentralized electric power supply can also mean a decentralized network structure. Such a decentralization of the network is only possible with decentralized generation units.

In our study, in case of a high proportion of distributed generation we also assume a certain degree of decentralization of the grid.

1.2. Expectations for decentralized electricity generation

Very different expectations are associated with decentralization. They range from economic [7] and above all ecological benefits up to and including an improvement of sustainability in the broadest sense [1].

The following have been mentioned as benefits of decentralized electricity generation:

‘‘On-site production avoids transmission and distribution costs [...]. On-site power production by fossil fuels generates waste heat that can be used by the customer.’’ (This is called ‘‘cogeneration’’ or ‘‘combined heat and power’’ (CHP).) ‘‘Distributed generation may also be better positioned to use inexpensive fuels such as landfill gas’’ [1].

A life cycle assessment [10,11] shows that CHP leads to savings in primary energy consumption and to lower emissions of CO_2 and pollutants (apart from non-methane hydrocarbons (NMHC)).

It can also help to avoid expensive investments in the power distribution network [8,12,13] and may facilitate the application of renewable energy sources and efficient technologies [12].

Under certain conditions, it may increase the reliability of the supply and reduce the vulnerability of the energy supply system [13].

However, distributed generation may also have disadvantages.

According to the International Energy Agency [1] ‘‘DG has higher unit capital cost per kilowatt than a large plant. It has lower fuel economy, unless used in CHP mode, and uses a more limited selection of fuels. For photovoltaic systems, operating costs are very low but high capital costs make it uncompetitive. ‘‘Studies by the Congressional Budget Office (CBO) [12] and the U.S. Department of Energy [13] also point to higher costs as a possible disadvantage.

Distributed generation may reduce the stability and quality of supply or, if this is to be avoided, may require costly investments [1,8,9,12].

Whether distributed generation has a positive or negative influence on stability of supply depends on the way in which the decentralized plants are operated. An operating mode in which CHP plants are controlled by the heat demand and wind energy converters by the available wind will reduce the stability of supply. In order to improve supply stability, generation must be controlled by the demand for electricity [1].

1.3. Previous studies on the advantages and disadvantages of distributed generation

Previous studies on the advantages and disadvantages of decentralized electricity generation include, on the one hand, those that deal with selected issues of distributed generation (DG) [1,12–14]. These studies leave unanswered the question of whether these issues can be regarded as sufficiently complete for an evaluation of decentralized electricity generation or whether additional issues must be considered for a comprehensive assessment. They do not proceed from specific energy

supply scenarios in which decentralized generation is represented as a building block in the energy supply.

On the other hand, Alanne and Saari [15] place their assessment of DG in the sustainability context but decide not to become involved in ‘‘comparing the performance of different energy systems in terms of sustainability indicators’’. On the contrary, they examine the extent to which DG can contribute to making the energy supply system itself sustainable in the sense that it will be able to fulfil future demands.

Although the aim of the EurEnDel study [16] was not a comprehensive assessment of sustainability, nevertheless, the study developed various scenarios [17] and investigated the question of which technological developments in the various scenarios display ‘‘robust’’ benefits or could at least be beneficial in some areas, also including DG.

In Bohnenschäfer et al. [18], sustainability criteria from various sources in the literature are compared and by applying an approach from an earlier study [19] a set of criteria and minimum demands are compiled. Experts from seven institutions were charged with the task of providing a qualitative evaluation of the performance of 16 selected electricity generating technologies, including 5 decentralized technologies, in comparison to the reference technology ‘‘combined cycle plant’’ for these criteria. Two of the institutions contacted did not wish to participate in this survey because in their opinion the performance of electricity generating systems depends decisively on boundary conditions such as upstream processes (i.e. all the processes necessary for the production of the technology and the extraction of raw materials), operating conditions and energy mix, which were not specified in this study. The study compared the assessments made by the various experts and came to the conclusion that they do not display any major differences. The aggregated overall evaluation, in which all the criteria get the same weight, is indifferent with respect to practically all criteria since the advantages of some of the criteria cancel out the disadvantages of others. The complete spectrum of advantages and disadvantages only becomes apparent on the level of the individual criteria. No consideration is given to the interactions of the technologies with the overall national economy and society as a whole.

Longden et al. [20] proceed from scenarios and use a wide range of criteria. They evaluate whether it is better to construct plants for producing energy from waste on a centralized or decentralized basis. However, the results cannot be transferred to distributed generation in general.

Radgen and Oberschmidt [21] evaluate the properties of several CHP technologies using a multicriteria method, but, like Bohnenschäfer et al. [18], only the technology itself with no respect to scenarios. The study includes only large centralized CHP plants and no distributed generation.

There is thus still no study that evaluates DG both in the context of specific scenarios and also its performance with respect to a comprehensive set of sustainability criteria.

The present article indicates the advantages and disadvantages of DG obtained on the basis of comprehensive sustainability criteria in the context of specific scenarios.

Section 2 describes the procedure, the scenarios and the sustainability criteria as well as the methodology of the study. The results are presented in Section 3, while Section 4 discusses the findings and Section 5 contains the conclusions.

2. Methodology and procedure

The task in hand makes certain demands on the methodology:

(a) Depending on the technical and economic boundary conditions, the advantages and disadvantages of decentralized electricity generating plants are different and have different effects. It is therefore not sufficient to simply consider all decentralized electricity generating technologies, but they must rather be considered when embedded in scenarios. This demand was also mentioned in Bohnenschäfer et al. [18].
(b) The goal of ‘‘sustainability’’ is multidimensional [22] so that the methodology must be capable of reflecting this multidimensionality.

The present studies are therefore based on (a) four scenarios compiled with the participation of societal actors and representing conceivable future visions. They differ not only with respect to the degree of decentralization of the electricity supply but also with respect to other technical, economic and social conditions.

With respect to (b), the evaluation paradigm ‘‘sustainability’’ was also operationalized with the participation of societal actors in a set of criteria structured in a value tree.

The scenarios and the value tree were presented to scientific experts who had the task of assessing the extent to which these criteria were fulfilled in the four scenarios.

2.1. Starting point for the investigations

2.1.1. Scenarios

In three 2-day moderated scenario workshops with 25 participants from science and society at large, four energy scenarios were developed with a spatial focus on Germany and a time horizon of 2025 [23]. The Battelle Scenario Inputs to Corporate Strategy (BASICS) method was used to generate scenarios of the likely determinants. According to the typology drawn up by Börjeson et al. [24], these are explorative scenarios. They integrate demographic, economic, societal and technological knowledge.

In the following, the essential aspects of the scenarios are described which are of significance for evaluating decentralization.

- Scenario A:
  - societal consensus on priority of environmental protection,
  - energy mix with high percentage of gas and renewables,
  - high contribution of distributed generation to total electricity generation,
  - great portion of distributed generation is integrated in virtual power plants,
  - movement away from urban towards rural areas.

- Scenario B:
  - government actively involved in protecting climate and environment,
  - energy mix with high percentage of gas and renewables,
  - contribution of distributed generation lower than in Scenario A,
  - only few virtual power plants,
  - in settlement structure, preference given to developments on the outskirts of urban areas.
- Scenario C:
  - government encourages the success of German enterprises by heavy investment in innovation and technology policy, support for environmental and health remains moderate and is of secondary importance,
  - energy mix with high percentage of coal and nuclear,
  - investments made for modernizing centralized plants, low proportion of decentralized facilities,
  - in settlement structure, preference given to developments on the outskirts of urban areas.
- Scenario D:
  - little government involvement,
  - energy mix with high percentage of coal and nuclear,
  - little investment, old plants continue to be operated, low proportion of decentralized plants,
  - in settlement structure, preference given to developments in urban areas.

Table 1 shows the percentage of decentralized plants in electricity generation in the various scenarios.

2.1.2. Value tree

The sustainability criteria which were to be used to evaluate the scenarios were compiled by a value tree analysis [25]. A value tree was set up by means of interviews with 11 representatives of associations in the energy economy, environmental and consumer protection as well as with trades unions. This value tree contains all the criteria of a sustainable energy supply regarded as important by the associations. The goal of ''sustainability'' was differentiated on three levels. On the first level, the objective was described by the five areas of environmental protection, health protection, security of supply, economic aspects and social aspects. On the second level, between 4 and 8 criteria were assigned to each area—31 in total. And on the third level, they are divided into a total of 86 criteria. Fig. 1 shows a section of this value tree in which only those criteria are depicted that have an influence on decentralization.

2.2. Procedure

The four scenarios were evaluated by 11 scientific experts by means of the sustainability criteria. In selecting the scientific experts, consideration was given to the fact that their individual expertise should, if possible, cover all the criteria of the value tree when combined. In order to ensure a plurality of experts at least to a certain extent, in the fields of environmental protection, economics and security of supply several experts were charged with the same tasks.

There are several multicriteria methods which have already been successfully applied in energy planning. One of these is the AHP approach (analytic hierarchy process) [26,27] which has been widely used and verified by comparison with other methods [28]. On the basis of this approach, the AHP scale was used to evaluate the scenarios. The AHP method permits paired comparisons between the scenarios using a standardized evaluation format. The AHP approach was expanded in order to make explicit any disagreement among the experts. Each expert had to specify what he based his evaluation on. It was thus possible to categorize and reveal differences between the evaluations of several experts. The scientific experts received standardized data sheets to enter their evaluations and were given detailed instructions. The experts were set the following tasks:

1. The four scenarios had to be evaluated on the lowest level of the value tree. If the criteria were still at too high a level of aggregation then they had to be operationalized in a first step so that it was possible to provide specific information.
2. Wherever possible a quantitative assessment was required. As a refinement of this assessment, it was possible to specify an area which, in the expert's opinion, probably contained the values and also to indicate the most probable value.
3. If it was not possible to specify a quantitative value then in accordance with the AHP paired comparisons should be made for all four scenarios with respect to the relevant criterion on the verbal rating scale with nine steps in both directions [e.g. 29]. Furthermore, verbal evaluations had to be made to illustrate the differences between the scenarios.
4. The rating confidence for each evaluation had to be given on a five-step scale (0 = I have no confidence in my judgment; 5 = I have complete confidence in my judgment)
5. Reasons had to be given for all assessments. The basis for the respective assessments had to be made clear, the assumptions and hypotheses on which the judgment was based and what scenario elements were used to make the judgment.

Table 1
Contribution of distributed generation to the electricity generation in the scenarios

Technology	Scenario A	Scenario B	Scenario C	Scenario D
CHP (gas-fired) 5...100 kW_{el}	5%	3%	3%	2%
CHP (gas-fired) < 5 kW_{el}	2.5%	1%	0.5%	0%
distributed generation from renewables	15%	10%	5%	5%

CHP: combined heat and power.

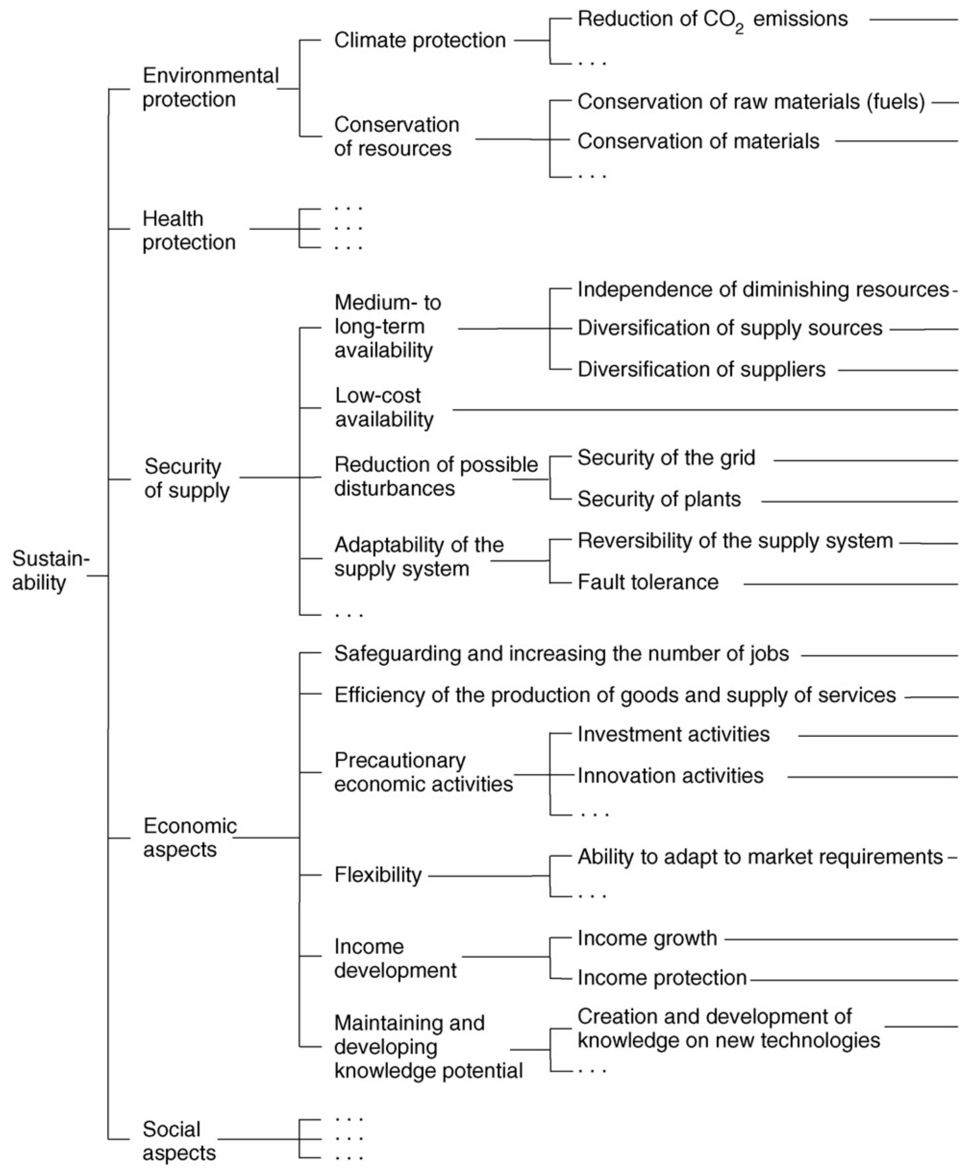

Fig. 1. Partial view of the value tree.

6. After all the assessments had been made, the experts had to review their own opinions in view of the evaluations made by the other experts.

The experts assessed the scenarios as a whole and not only the isolated aspect of decentralization. This is necessary since any change in the electricity supply system would have repercussions on other fields of human activity, which would also affect the criteria. The grading of the scenarios performed by the experts in the form of paired comparisons therefore form an integral assessment. As a result an assessment of the impacts of distributed generation was obtained according to the conditions prevailing in the scenarios under consideration. On the basis of the justifications put forward by the experts for their evaluations it was possible to identify the influence of decentralization on the assessment of the criteria.

2.3. Analysis

If there were only marginal differences between the assessments by the various experts the evaluations were aggregated.

The geometric mean was used for the aggregation, as recommended by Saaty [30]. From the evaluation of a large number of sources, Budescu et al. [31] conclude that "some form of averaging is almost always nearly optimal". Münnich et al. [32] show that important demands on the aggregation procedure can be fulfilled by quasilinear means. The group of quasilinear means includes in particular the arithmetic mean and geometric mean. The "Team Expert Choice" software, which implements the AHP for several assessors, also forms the geometric mean of the paired comparison factors [33].

In the case of different expert assessments, the reasons for the discrepancies were analysed by the authors. On the one

hand, these may represent differences in the assessment of the same aspect, for instance, if an expert is of the opinion that small-decentralized plants are beneficial for the security of the grid, whereas another expert takes the view that they reduce this security. In such cases, the evaluations of the individual experts are given separately in order to highlight the differences.

On the other hand, differences may be due to the fact that the experts' evaluations are based on different, complementary information. An example is the criterion ''efficiency of the production of goods and supply of services''. In this case, one expert justifies his assessment by his view that regulatory instruments are more effective than free market mechanisms, whereas the second expert considers that the high capital expenditure for the construction of new plants reduces efficiency, and a third expert uses consumer price developments as a yardstick for efficiency. These different evaluations are not mutually exclusive, but rather complement each other so that in spite of the different scenario rankings provided by the experts their evaluations were aggregated.

3. Results

3.1. Performance of the scenarios with respect to the criteria

As a rule, the results of the scenario evaluations are paired comparisons which indicate the relative differences between the scenarios. The experts found it impossible to make an assessment with respect to the absolute degree to which the criteria were fulfilled. This was due to a number of reasons.

1. Many factors are only given qualitatively in the scenarios or are uncertain.
2. The framework for the expert judgments is electricity generation. But for sustainability assessment, for example, the total amount of emissions is relevant and electricity generation is not the only source of emissions. Other important sources of emissions mentioned by the experts are outside the frame of reference of the scenarios, such as road traffic and agriculture. In part, the experts assumed that these sources would cause roughly the same level of emissions as today, and in part that the current trend towards emission reduction would continue analogously. They did, however, note that decentralization may lead to an increase in road traffic and that the use of renewable energy sources may result in an intensification of agriculture.

In the following, the results of the expert judgments are given for the respective sustainability criteria.

In the field of *environmental protection* the impacts of distributed generation are quite apparent. They relate to three criteria:

- ''reduction of CO_2 emissions'' from households, manufacturing industry and companies in the supply sectors,
- ''conservation of raw materials'', i.e. economical use of fuel for the production of supply services for production and operation: this refers to sources of primary energy such as coal, natural gas and uranium,
- ''conservation of materials'', i.e. economical use of materials required during the construction, operation or dismantling of supply installations (power plants, wind turbines, heating plants), e.g. sand, minerals or metals.

Distributed generation has a positive effect on the ''conservation of fuels'' and the associated ''CO_2 emissions'' since it encourages the application of combined heat and power (CHP) and thus leads to lower fuel consumption. CO_2 emissions are additionally reduced since decentralized plants can only be operated with gas or a similar high-quality fuel with a low carbon content, whereas a large proportion of the centralized plants are coal-fired. In contrast, as the most important influence on the ''conservation of materials'' distributed generation has an obviously negative effect since the construction of a number of small plants results in a greater consumption of materials than the construction of a few large plants. The integral evaluation of the scenarios with respect to these criteria is shown in Table 2.

The impacts in the *security of supply* sector are characterized by a number of conflicting influences and great uncertainty.

Dependence on natural gas, which is intensified by decentralized plants, is the main reason for the negative assessment of scenarios A and B for the ''diversification of suppliers'' criterion (the spatial distribution of reserves of the energy carrier).

Table 2
Performance of scenarios with respect to criteria from the sector of environmental protection

Criterion	Performance of Scenarios lower----------------------------higher by a factor of----------------- by a factor of .25----.5------1------2-------4
Reduction of CO_2 emissions	-----D-C--------------B----A---
Conservation of raw materials (fuels)	------DC--------------B-A------
Conservation of materials	------A------B----C---D--------

The table shows the relative performances of scenarios A–D as derived from the experts' assessments using the AHP paired comparisons method. The performance of each scenario is indicated by its position on a 31-step logarithmic scale. The centre of the scale indicates average performance. The leftmost/rightmost position indicates a performance which is a factor of 4 lower/higher than average.

Table 3
Performance of scenarios with respect to criteria from the sector of security of supply

Criterion	Performance of Scenarios lower----------------------------higher by a factor of------------------ by a factor of .25----.5------1------2-------4
Diversification of suppliers	------------B-A--C------------- D
Independence of diminishing resources	--------C-D---------B-A--------
Diversification of supply sources 4 experts 4 different assessments	---------A-----------C--------- B D
	----------C------B-----A------- D
	-------C---------B-----------A- D
	B ------A-----------C------------ D
Fault tolerance	--------D--C-------B---A-------
Security of the grid 4 experts 3 different assessments	-----A----B---------C----D-----
	---------C---------B---A------- D
	A ---------------B--------------- C D
Security of plants 3 experts 3 different assessments	-------A-----B------C---------- D
	----D---C-------------B---A----
	A ---------------B--------------- C D
Low-cost availability 4 experts 4 different assessments	-----A----B---------D----C-----
	-------A-------------C----D---- B
	--D--------C-------B--------A--
	B ------A-----------C------------ D
Reversibility of the supply system 4 experts 4 different assessments	--------D------A------B-------- C
	------C---------------B---A---- D
	------B-----------------A------ D C
	B ------A-----------C------------ D

The table shows the relative performances of scenarios A–D as derived from the experts' assessments using the AHP paired comparisons method. The performance of each scenario is indicated by its position on a 31-step logarithmic scale. The centre of the scale indicates average performance. The leftmost/rightmost position indicates a performance which is a factor of 4 lower/higher than average. If two or more scenarios are assigned to the same step on the scale, they appear in a column in the appropriate place.

The dependence on natural gas also has a negative effect on the ''independence of diminishing resources'' (this criterion demands that resources which are finite in the long term, such as fossil energy carriers and rare metals, should be replaced), but this is more than compensated by an overall lower electricity consumption and a higher proportion of renewable energies.

With respect to an evaluation of the ''diversification of supply sources'' (which requires the most varied possible mix of different classical and renewable energy sources), the experts had different opinions on whether the positive effect of a high percentage of decentralized plants or the negative effect of a great dependence on natural gas would be more significant. With this criterion, two experts rated Scenario A, which had the highest proportion of decentralized plants, as particularly good, whereas two other experts rated it as particularly poor.

With respect to ''fault tolerance'', i.e. the ability of a supply system to fulfil its specific supply function even with a limited number of malfunctioning subsystems, components etc., decentralized plants were unanimously regarded as positive. According to the experts, decentralized plants increase fault tolerance since failure of one small plant would have a much smaller impact that than the failure of a large facility.

Similar arguments were put forward for the criteria ''security of the grid'' (avoidance of technical grid failures)

and ‘‘security of the plants’’ (avoidance of technical plant failures). Failure of a small plant has much less severe impacts than failure of a large facility. If, however, the decentralized plants are centrally controlled (so-called virtual power plant) then malfunctions of the central control may lead to similar impacts to that of failure of a large facility. On the other hand, decentralized plants without central control may lead to problems with grid stability. Two experts therefore put forward different assessments here. The third expert did not see any difference since it is ultimately a question of the specific technical design and the level of investment for increasing reliability as to whether distributed generation increases or reduces security of the grid and plants.

Higher material and labour costs for the construction and maintenance of decentralized plants has a negative impact on ‘‘low-cost availability’’ (of supply services). Opinion differed as to whether this can be compensated by lower fuel costs and other savings.

‘‘Reversibility of the supply system’’ was rated differently by different experts. On the one hand, small-decentralized plants were regarded as more flexible (easier to replace) than large centralized facilities. On the other hand, high capital expenditure is always practicably irreversible irrespective of whether it is made in decentralized plants, centralized facilities or in reconstructing the grid.

The integral evaluation of the scenarios with respect to these criteria is shown in Table 3.

In contrast, with respect to *economic aspects*, investments in decentralized plants are rated positively and have the greatest influence concerning the criteria of ‘‘investment activities’’ (regular investments according to the state of the art to prevent even higher follow-up costs) and ‘‘innovation activities’’ (continuous R&D activities and also the application of new technologies in companies in the supply sectors) as well as the ‘‘establishment and development of know-how on new technologies’’.

The high labour costs regarded as detrimental in the field of security of supply for ‘‘low-cost availability’’ have a positive side with contributions to ‘‘safeguarding and increasing the number of jobs’’ and ‘‘income growth’’ (influence of supply sectors on the growth of national income) and ‘‘income protection’’ (influence of the supply sectors on the constancy of national income). According to the experts, the supply sectors, however, only have a marginal influence on employment and incomes, while the main influence is that of general economic growth.

With respect to the ‘‘ability to adapt to market requirements’’ (ability of companies in the supply sector to adapt with respect to the requirements of both supply and demand), decentralized generation is the main positive influence, although this largely concerns administrative and economic decentralization rather than technical decentralization.

Finally, opinion differs as to the ‘‘efficiency of the production of goods and supply of services’’. On the one hand, administrative and economic decentralization and also lower fuel consumption increases efficiency, but on the other hand efficiency is reduced in the case of distributed generation due to higher investment and maintenance costs.

The integral evaluation of the scenarios with respect to these criteria is shown in Table 4.

Table 4
Performance of scenarios with respect to criteria from the sector of economic aspects

Criterion	Performance of Scenarios lower-----------------------------higher by a factor of------------------ by a factor of .25----.5------1------2-------4
Investment activities	-----C-----D--------B---A------
Innovation activities	-------D------C--A----B--------
Creation and development of knowledge on new technologies	------D----C-------B----A------
Safeguarding and increasing the number of jobs	------D-------B---C---A--------
Income growth	-------D----B------C--A--------
Income protection	------D----------B--A---------- C
Ability to adapt to market requirements	----------D-C------A----------- B
Efficiency of the production of goods and supply of services	------D-----C-----B-----A------
3 experts 2 different assessments	------A----------------C------ B D

The table shows the relative performances of scenarios A–D as derived from the experts' assessments using the AHP paired comparisons method. The performance of each scenario is indicated by its position on a 31-step logarithmic scale. The centre of the scale indicates average performance. The leftmost/rightmost position indicates a performance which is a factor of 4 lower/higher than average. If two or more scenarios are assigned to the same step on the scale, they appear in a column at that step.

4. Discussion

4.1. Results

The experts' assessments show that distributed generation can fulfil the expectations associated with it, in particular it can make a contribution to climate protection, although it does involve certain disadvantages. Distributed generation does not have clear advantages in any of the sustainability dimensions.

In the field of *environmental protection*, distributed generation (CG) can reduce emissions of CO_2 and the consumption of primary energy carriers, which confirms the expectations mentioned in the literature [e.g. 1]. On the other hand, this leads to a higher consumption of materials for constructing the plants. This aspect is frequently overlooked. Strachan and Farrell [34] investigated other emissions and discovered that it depends on operating conditions and other technical details whether in this respect DG with combined heat and power (CHP) is more efficient than centralized electricity generation with distributed heating boilers.

With respect to *security of supply*, distributed generation increases dependence on natural gas and thus actually reduces security of supply. This aspect is also mentioned by Pepermans et al. [14].

Security of the grid and the plants is rated in different ways, both by the experts interviewed and also in the literature. Whether decentralized electricity generating plants reduce or increase grid stability depends on a number of technical details. On the one hand, the International Energy Agency [1] assumes that ''The reliability of electric power systems can be enhanced by distributed generation'', but, on the other hand, also lists a number of problems: ''voltage control'', ''reactive power'' and ''protection'', and finally argues that ''The main potential negative effect of distributed generation is an increased need for regulating power. This additional backup capacity will be needed if the DG technologies cannot be centrally controlled...''. De Joode and van Werfen [8] mention both advantages and disadvantages, e.g. ''(+) Installed (controllable) capacity increases and (−) changing power flows are hard to handle''.

With respect to *economic aspects*, the experts are in agreement with each other and with the literature [e.g. 1] that small-decentralized energy generating plants require greater capital investment than large centralized facilities. It is, however, uncertain whether the balance of capital costs for investment and achievable savings in primary energy consumption yields a net profit or not. This depends on the unknown developments of the money markets and the primary energy prices.

It is also consensus that small-decentralized electricity generation plants are more labour-intensive than large centralized facilities. Although it is true that they may create jobs and income in the electricity supply sector, they also increase the cost of supplying electric power. Doubt is cast upon the statement that on balance more jobs will be created since the increased cost of the electricity supply would divert purchasing power from other sectors. Pfaffenberger [35] pursues this argumentation with the example of renewable energies.

4.2. Methodology

In particular the following aspects of the methodology proved important and helpful:

- the embedding of decentralized technologies in the overall social scenarios,
- the application of a set of sustainability criteria developed by the societal actors involved and accepted by all parties,
- the involvement of several experts in order to analyse the uncertainty of their assessments,
- the analysis of the justifications put forward by the experts permitting differences in their assessments to be categorized,
- the application of relative paired comparisons, by means of which it was possible to handle the basic problem that many of the sustainability criteria could only be qualitatively assessed.

This shows that it is not enough merely to consider a technology or a technological trend in isolation, but rather that all anthropogenic and natural emissions as well as the existing loads should be included. It proved difficult to restrict the frame of reference of the scenarios to supply systems and settlement structure since this does not provide the possibility of giving consideration to interactions with other sectors such as the impacts of decentralization on the transport sector. In this respect, not even the relatively comprehensively defined scenarios used in our studies are sufficient.

The differentiated treatment by the experts is a useful basis for an overall assessment by societal actors and increases the transparency of the sustainability evaluation.

5. Conclusions

The results show that a decentralization of electricity generation with respect to sustainability cannot be rated as clearly positive or negative, as also pointed out by Alanne and Saari [15]. In some cases it has a positive effect on the sustainability criteria and in some cases a negative effect and sometimes the experts differ in their opinions. This finding underlines the necessity of applying a multicriterial method. The overall assessment depends on which of the criteria are rated as particularly pressing sustainability problems. Furthermore, many of the impacts depend to a considerable extent on the boundary conditions of the scenarios, such as the operating conditions of the decentralized plants or on macroeconomic conditions.

The results, moreover, show that suitable measures must be taken for the technical implementation of distributed generation in order to ensure stability and security of the grid, cf. de Joode and van Werfen [8] and Degner et al. [36]. Further research is being conducted on this aspect, see for example http://www.sedg.ac.uk/. Currently, distributed generation (DG) and renewable energy resources (RES) do not contribute to the

task of securing frequency and voltage on the grid, but with increasing contributions of such systems they will have to take over part of this task [37].

Finally, not only should centralized and distributed generation be combined [15], but different decentralized technologies should also be applied in order to compensate for their different advantages and disadvantages. For example, although solar and wind power can achieve great savings of fossil fuels and CO_2 emissions, they are not suitable for covering peak loads since they are not always available. In contrast, gas- or oil-fired decentralized electricity generating plants can be used to cover peak loads but they have higher fuel consumption and higher emissions.

Acknowledgement

The study was funded by the German Federal Ministry of Education and Research (BMBF) as part of the joint research project ''Integrated Microsystems for Supply'' within the focal framework of ''social-ecological research''.

References[1]

[1] IEA. Distributed generation in liberalised electricity markets. Paris: International Energy Agency (OECD/IEA); 2002.
[2] Lund H, Østergaard PA. Electric grid and heat planning scenarios with centralised and distributed sources of conventional. CHP and wind generation. Energy 2000;25:299–312.
[3] Lund H. Flexible energy systems: integration of electricity production from CHP and fluctuating renewable energy. IJETP 2003;1:250–61.
[4] Bohn D. Decentralised energy systems: state of the art and potentials. IJETP 2005;3:1–11.
[5] Enquete-Kommission ''Nachhaltige Energieversorgung unter den Bedingungen der Globalisierung und der Liberalisierung''. Schlussbericht. Bundestags-Drucksache, 14/9400. Berlin: Deutscher Bundestag; 2002. http://www.bundestag.de/parlament/gremien/kommissionen/archiv14/ener/schlussbericht/index.htm (verified May 25, 2007).
[6] Ackermann T, Andersson G, Söder L. Distributed generation: a definition. Elec Power Syst Res 2001;57:195–204.
[7] Feinstein CD, Orans R, Chapel SW. THE DISTRIBUTED UTILITY: a new electric utility planning and pricing paradigm. Annu Rev Energy Environ 1997;22:155–85.
[8] de Joode J, van Werven M. Optimal design of future electricity supply systems. Presented at the IAEE European Energy Conference 2005, Bergen, Norway, August 28–30, 2005, Report ECN-RX–05-195. Petten, NL: Energy research Centre of the Netherlands; 2005. http://www.ecn.nl/docs/library/report/2005/rx05195.pdf (verified May 30, 2007).
[9] Peacock AD, Newborough M. Impact of micro-combined heat-and-power systems on energy flows in the UK electricity supply industry. Energy 2006;31:1804–18.
[10] Pehnt M. Ganzheitliche Bilanzierung von Brennstoffzellen in der Energie- und Verkehrstechnik. Düsseldorf: VDI-Verlag; 2002.
[11] Pehnt M. Assessing future energy and transport systems: the case of fuel cells. Part 2. Environmental performance. Int J LCA 2003;8:365–78.
[12] CBO Prospects for Distributed Electricity Generation. Washington, DC: The Congress of the United States, Congressional Budget Office; 2003. http://www.cbo.gov/ftpdocs/45xx/doc4552/09-16-Electricity.pdf (retrieved May 31, 2007).
[13] U.S. Department of Energy. The potential benefits of distributed generation and rate-related issues that may impede their expansion. A Study Pursuant to Section 1817 of the Energy Policy Act of 2005. 2007. http://www.oe.energy.gov/DocumentsandMedia/1817_Study_2_05_07_(2).pdf (retrieved May 31, 2007 from page http://www.oe.energy.gov/epa_sec1817.htm).
[14] Pepermans G, Driesen J, Haeseldonckx D, Belmans R, D'haeseleer W. Distributed generation: definition, benefits and issues. Energy Policy 2005;33:787–98.
[15] Alanne K, Saari A. Distributed energy generation and sustainable development. Renew Sustain Energy Rev 2006;10:539–58.
[16] EurEnDel. EurEnDel - Technology and Social Visions for Europe's Future. A Europe-wide Delphi Study. Final Report. Berlin: IZT - Institute for Futures Studies and Technology Assessment (http://www.izt.de); 2004. http://www.izt.de/pdfs/eurendel/results/eurendel_final.pdf on page http://www.izt.de/eurendel/survey_results/index.html (verified May 9, 2007).
[17] Velte D. The EurEnDel Scenarios. Working document. Berlin: IZT - Institute for Futures Studies and Technology Assessment (http://www.izt.de); 2004. http://www.izt.de/pdfs/eurendel/results/eurendel_scenarios.pdf on page http://www.izt.de/eurendel/survey_results/index.html (verified May 9, 2007).
[18] Bohnenschäfer W, Koepp M, Scheelhaase JD, Schlesinger M. Perspektiven für elektrischen Strom in einer nachhaltigen Entwicklung. UBA-FBNr 000468. Climate Change, 07/03. Berlin: Umweltbundesamt; 2003. http://www.umweltdaten.de/publikationen/fpdf-l/2432.pdf (verified April 17, 2007).
[19] PROGNOS-AG Basel. PVC und Nachhaltigkeit - Systemstabilität als Maßstab, ausgewählte Produktsysteme im Vergleich. Köln: Deutscher Institutsverlag; 1999.
[20] Longden D, Brammer J, Bastin L, Cooper N. Distributed or centralised energy-from-waste policy? Implications of technology and scale at municipal level. Energy Policy 2007;35:2622–34.
[21] Radgen P, Oberschmidt J. Multidimensional assessment of heat and power supply technologies with a special focus on CHP. German Heat and Power Association - AGFW - (Frankfurt, Main): 10th International Symposium on District Heating and Cooling. September 3–5, 2006, Hannover: Conti-Campus Hannover University of Technology; 2006. http://publica.fraunhofer.de/eprints/N-48358.pdf (retrieved July 17, 2007).
[22] World Commission on Environment and, Development. Our common future. Oxford: Oxford University Press; 1987.
[23] Karger CR, Hennings W, Jäger T. Chancen und Risiken zukünftiger netzgebundener Versorgung. Jülich: Forschungszentrum Jülich GmbH; 2006.
[24] Börjeson L, Höjer M, Dreborg K-H, Ekvall T, Finnveden G. Scenario types and techniques: towards a user's guide. Futures 2006;38:723–39.
[25] von Winterfeldt D, Edwards W. Decision analysis and behavioral research. Cambridge: Cambridge University Press; 1986.
[26] Saaty TL. The analytic hierarchy process. Pittsburgh, PA: RWS Publications; 1990.
[27] Saaty TL, Vargas LG. Models, methods, concepts & applications of the analytic hierarchy process. Boston: Kluwer; 2000.
[28] Pohekar SD, Ramachandran M. Application of multi-criteria decision making to sustainable energy planning—a review. Renew Sustain Energy Rev 2004;8:365–81.
[29] Saaty TL. How to make a decision: the analytic hierarchy process. EJOR 1990;48:9–26.
[30] Saaty TL. The seven pillars of the analytic hierarchy process. Creative Decisions Foundation; 1999. http://www.creativedecisions.net/papers/papers_etc/SevenPillars.doc (verified April 16, 2007).
[31] Budescu DV, Rantilla AK. Confidence in aggregation of expert opinions. Acta Psychol 2000;104:371–98.
[32] Münnich Á, Maksa G, Mokken RJ. Collective judgement: combining individual value judgements. Math Social Sci 1999;37:211–33.
[33] Meixner O, Haas R. Computergestützte Entscheidungsfindung: Expert Choice und AHP - innovative Werkzeuge zur Lösung komplexer Probleme Frankfurt a. M.. Wien: Redline Wirtschaft bei Ueberreuter; 2002 .
[34] Strachan N, Farrell A. Emissions from distributed vs. centralized generation: the importance of system performance. Energy Policy 2006;34: 2677–89.

[1] *Note*: If a reference for which an URL is given is no longer available on the Internet, it can be obtained from the authors on request.

[35] Pfaffenberger W, Jahn K, Djourdjin M. Renewable energies – environmental benefits, economic growth and job creation. Case study paper, published in Saxe & Rasmussen (2006): Green Roads to Growth. Bremen: bremer energie institut; 2006. p. 424–89. http://www.bei.uni-bremen.de/download/renewable_energies.pdf (verified May 30, 2007).

[36] Degner T, Schmid J, Strauss P. DISPOWER - distributed generation with high penetration of renewable energy sources. Final Public Report. Kassel: ISET e.V.; 2006. http://www.iset.uni-kassel.de/dispower_static/documents/fpr.pdf (verified March 19, 2007).

[37] Lund H. Electric grid stability and the design of sustainable energy systems. Int J Sustain Energy 2005;24:45–54.

Cornelia R. Karger (Dipl. Psych., psychologist) is a senior scientist with the Programme Group Humans, Environment, Technology (MUT) at Research Centre Juelich (FZJ), Germany. She is responsible for the research focus management of innovations in MUT. Based on multi-year investigations in empirical and analytical technology assessment, she develops and tests approaches for improved communication and implementation of the concept of sustainable development and explores management concepts for new technologies.

Wilfried Hennings (Dipl.-Ing. in electrical engineering) has formerly been working in the area of risk and safety analyses for technical systems. He now is a scientist with MUT and works in the areas of ''management of innovations'' and ''assessment and handling of uncertainties and risk''.